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ENERGY TRANSFER RATES OF AN INTEGRATED LIFE SUPPORT SYSTEM DURING MANNED AND INTERMITTENTLY MANNED TESTS

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16. Abstract The identification and distribution of thermal and electrical energies within a typical life support system have been determined from data obtained from manned and intermittently manned tests of an integrated life support system (ILSS) at the Langley Research Center. Less than one-half of the energies supplied to the ILSS were directly used for its operation, with the remainder being lost as heat within the equipment plumbing and the test-chamber atmosphere or transferred through the test-chamber wall. The normal ILSS cyclic subsystem and unit operation and the energy coupling between thermal transport fluids produced minor fluctuations in the test-chamber atmosphere temperature. These findings are significant for the development of subsystem designs, fluid transport plumbing, and accessory equipment to improve energy utilization and demands of regenerative life support systems.			
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ENERGY TRANSFER RATES OF AN INTEGRATED LIFE SUPPORT SYSTEM DURING MANNED AND INTERMITTENTLY MANNED TESTS

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SUMMARY

An energy transfer study of an integrated life support system (ILSS) at the Langley Research Center during manned and intermittently manned tests has shown that approximately 10 kW of power in the form of electrical and thermal energies was supplied to the ILSS. Only 35 percent of these energies was directly utilized in the operation of the ILSS. The remaining 65 percent was lost as heat within the equipment plumbing and the test-chamber atmosphere or was transferred through the test-chamber wall. Controllers on the air-conditioning unit were found to have sufficient response to prevent fluctuations greater than 1.66°K (3°F) in the test-chamber atmosphere temperature. It was determined that the fluctuations originated from cyclic subsystem operation and coupling between thermal transport fluids. Some daily average and short-term transient energy transfer rates of the thermal fluids were also determined. The study involved the use of an automated data acquisition system and the development of computerized data processing techniques. Overall accuracy of the data management system was found to be within acceptable limits.

INTRODUCTION

Manned space travel lasting several months or years will require life support equipment and processes quite unlike those of the Mercury, Gemini, and Apollo spacecraft. Instead of carrying onboard sufficient expendable stores of materials to sustain human life, volume and weight constraints require that regenerative processes be utilized to recover and reuse essential supplies such as oxygen and water (ref. 1). These processes require a constantly available, relatively large supply of energy and a suitable means of rejecting waste energy.

Methods of regeneration are many and varied (ref. 2). It is necessary to determine and understand the energy utilization of each method to permit its design and integration into a complete operational life support system that uses the energy sources and sinks of the spacecraft. Although energy demands have been rigorously analyzed (refs. 3 to 6), these analyses have basically been theoretical and for steady-state conditions. The

periodic nature of the energy being transferred to and from all life support equipment in a complete life support system has not been studied, but must be known before vehicular integration is possible.

An integrated life support system (ILSS), designed for a four-man crew and an operational life of 1 year with 90-day resupply, was tested at the Langley Research Center in a manned and intermittently manned mode for 28 and 4 days, respectively. The manned test was performed May 20 through June 17, 1968, and the 4-day intermittently manned test was made during the week beginning October 28, 1968. Operation of the ILSS with and, essentially, without a crew in the test chamber permitted an evaluation of human contaminant and thermal loading as related to the operational characteristics of life support equipment in an integrated mode. Another objective of the tests was to obtain information necessary for determining energy balances across major subsystems and units. Sufficient measurements were taken to allow a comprehensive evaluation of energy utilization by the life support system and supporting equipment. The present paper has been prepared to report the results of this evaluation.

SYMBOLS

Values are given in both SI and U.S. Customary Units. The measurements and calculations were made in the U.S. Customary Units.

a, b, c	polynomial coefficients
c_p	specific heat of a substance at constant pressure, J/kg-°K (Btu/lb-°F)
h_d	heat of dissociation for electrolysis unit, J/kg (Btu/lb)
h_L	latent heat of condensation of water, J/kg (Btu/lb)
h_r	heat of reaction of carbon dioxide gas in Sabatier reactor, J/kg (Btu/lb)
m	mass, kg (lb)
\dot{m}_v	condensate collection rate, kg/s (lb/hr)
\dot{m}_r	carbon dioxide reaction rate in Sabatier reactor, kg/s (lb/hr)
\dot{m}_{O_2}	electrolysis-unit oxygen production rate, kg/s (lb/hr)

N	number of men in ILSS test chamber during testing
ΔP	pressure differential
Q	quantity of energy, J (Btu)
\dot{Q}	energy transfer rate, J/s (Btu/hr)
$\Delta \dot{Q}_d$	change in energy transfer rate due to dissociation in water electrolysis, J/s (Btu/hr)
\dot{Q}_L	latent thermal energy transfer rate for ILSS test chamber and crew, J/s (Btu/hr)
$\Delta \dot{Q}_r$	change in energy transfer rate of reactants in Sabatier exothermic reaction, J/s (Btu/hr)
\dot{Q}_S	sensible energy transfer rate of crew, J/s (Btu/hr)
T	temperature of an energy transport medium, $^{\circ}\text{K}$ ($^{\circ}\text{F}$)

Subscripts:

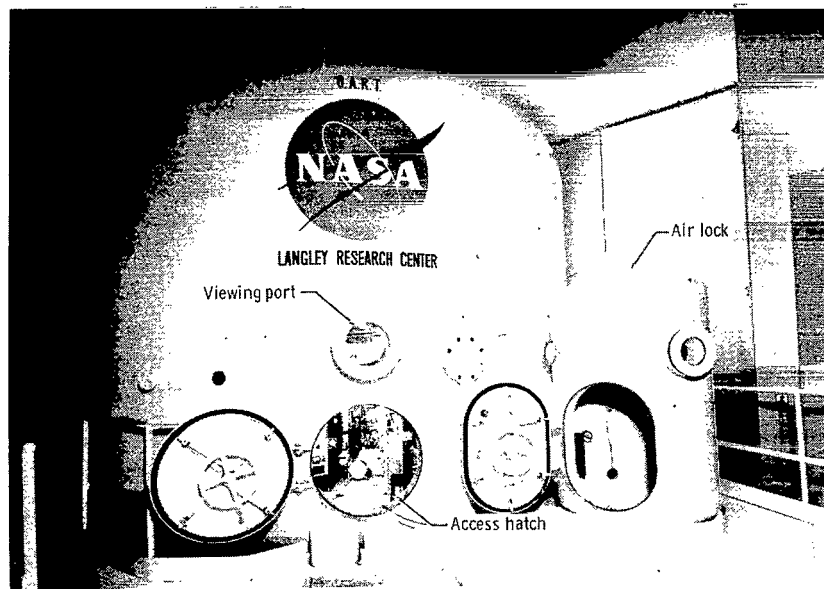
c	process cooling fluid
e	electricity
h	process heating fluid
l	losses
ll	test-chamber lower level
w	wall

INTEGRATED LIFE SUPPORT SYSTEM AT LANGLEY RESEARCH CENTER

Description of Test Chamber

Figure 1 is a photograph of the ILSS test chamber, a cylindrical 1.27-cm-thick (0.5-inch) steel enclosure measuring 5.59 meters (220 inches) in height by 5.59 meters

(220 inches) in diameter. The test chamber acts as an impervious barrier to the interchange of environments inside and outside the chamber. It also contains the life support equipment for a four-man crew. There are two levels in the test chamber. Equipment on the upper level supports functions such as eating, sleeping, and personal hygiene. Control of test-chamber atmospheric conditions (including temperature, oxygen partial pressure and contaminant concentrations, total pressure, and humidity) is provided by equipment on the lower level. Also on the lower level is equipment to recover useful water from urine, wash water, and humidity condensate. A detailed discussion of the functional aspects of the equipment (subsystems) may be found in references 3 and 7.



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Figure 1.- Test chamber of an integrated life support system at the Langley Research Center.

All the subsystems are integrated by function; that is, the mass-product outputs of one subsystem become inputs of another. Subsystem integration on a mass-product basis is pictured in figure 2. Photographs of the major subsystems are shown in figure 3. Subsystems are also integrated by common energy sources and sinks. A silicone-base oil is used to provide a portion of the process heating, whereas a glycol-water mixture is used for heat rejection. Tubing to transport these fluids between subsystems can be seen in figure 3.

Three types of electrical power are utilized within the test chamber: (1) 28 volts of regulated dc power, (2) three-phase 400-Hz ac power at 208 volts per phase, and (3) three-phase 60-Hz ac power at 115 volts per phase.

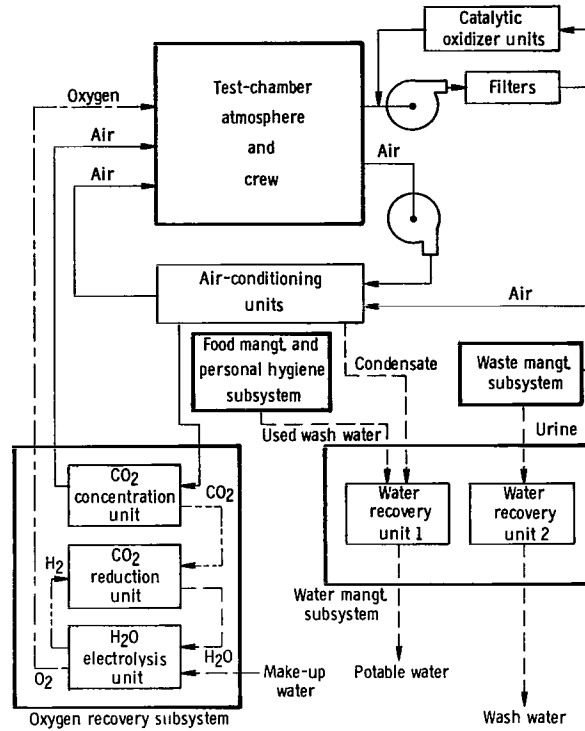
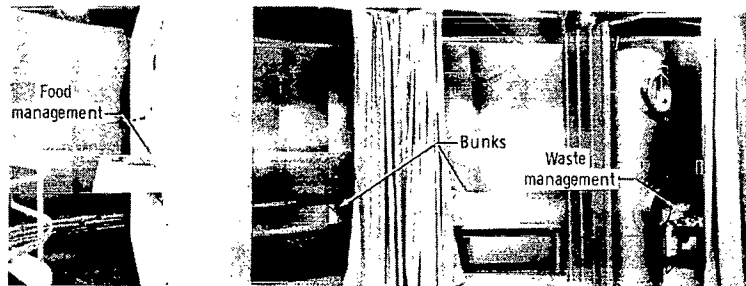
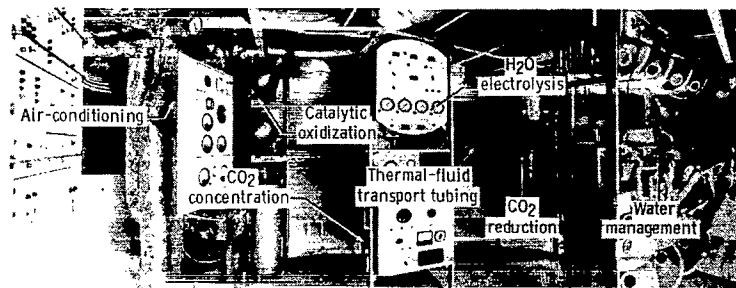


Figure 2.- ILSS subsystem integration on a mass-product basis.



(a) Upper level.



(b) Lower level.

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Figure 3.- Panorama of ILSS test-chamber interior.

External Energy Sources and Sinks

Subsystem energy demands are met by thermal transport fluids and electricity. These energies originate externally to the test chamber and are transported to it. Electrical conductors and fluid transport tubing pass into the test chamber through bulkhead fittings.

Heating cart. - The heating cart, shown schematically in figure 4, circulates a hot fluid which simulates waste heat that would be rejected from a Brayton cycle electric power system. There are three essential components in the heating cart: (1) immersible electrical heaters, (2) a centrifugal circulation pump, and (3) a fluid temperature control circuit. Temperature of the heating fluid is elevated by the heaters and maintained at a preselected level by the temperature-circuit controllers. The circulation pump forces the fluid through tubing and subsystems back to the heating cart. For normal ILSS operation the cart circulates fluid at temperatures of 450° to 464° K (350° to 375° F) to the subsystems at a rate of up to 0.0378 kg/s (300 lb/hr).

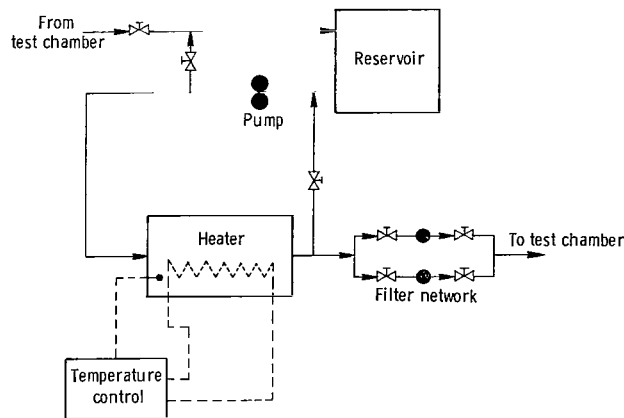


Figure 4.- Schematic diagram of heating fluid supply cart.

Electrical power. - One of the items supplying power to the ILSS is a 400-Hz motor generator set. It operates from building power and delivers three-phase 400-Hz ac power at 208 volts per phase.

Four direct-current power supplies provide 28 volts of regulated dc power from building power. Each of three modules in the oxygen-recovery-subsystem electrolysis unit has a separate direct-current power supply. All other ILSS direct-current requirements are met by the fourth power supply.

The third type of electrical power supplied to the ILSS is obtained from three-phase 60-Hz ac, 115-volts-per-phase electricity available from building power.

Cooling cart.- Incoming energy to the ILSS that is not converted into useful work must be removed in sufficient quantity to keep the test-chamber air at a tolerable temperature. A dual compressor refrigeration unit shown schematically in figure 5 removes heat from a glycol-water-mixture process cooling fluid that is circulated through the subsystems. The cooling cart contains a centrifugal pump to circulate the fluid at flow rates up to 0.227 kg/s (1800 lb/hr). The cart removes sufficient heat to keep test-chamber fluid inlet temperature near 272°K (30°F). Unlike a space radiator, which is the flight system element simulated by the cooling cart, the cart rejects its heat through a refrigeration-circuit heat exchanger to a water sink. Ultimately, the heat is given up to outdoor air by an evaporative cooler.

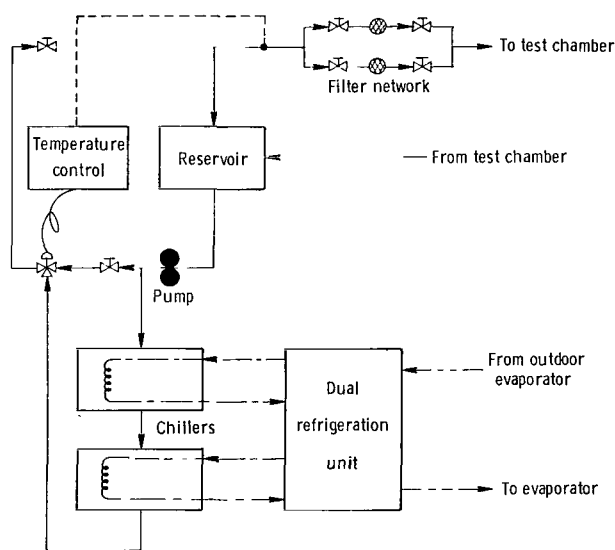


Figure 5.- Schematic diagram of cooling fluid supply cart.

Energy Distribution

Once inside the test chamber, energy transport fluids are distributed among subsystems as illustrated in figure 6. The distribution of electricity is not shown, but subsystem electrical requirements are presented subsequently.

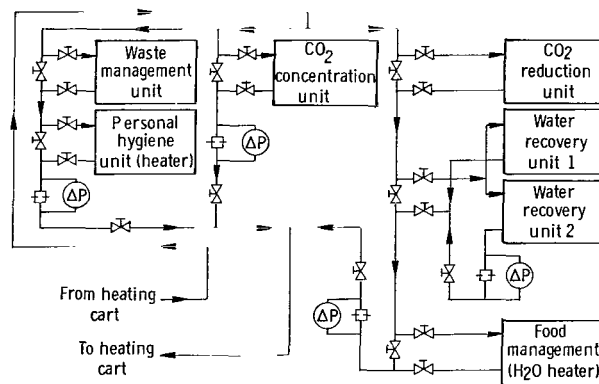
Heating fluid.- The heating fluid network depicted in figure 6(a) has three parallel branches. This configuration is necessary because the three units directly downstream of the point of branching have high-fluid-inlet-temperature requirements. Two of the branches have subsystems that may operate with lower fluid-inlet temperatures. Thus, a series arrangement can be used within these branches. For example, water recovery units are paralleled from a major network branch but are in series with the CO_2 reduction

unit. Thermal energy demands of the CO₂ concentration unit are so large and cyclic that other subsystems cannot operate on the same branch with it.

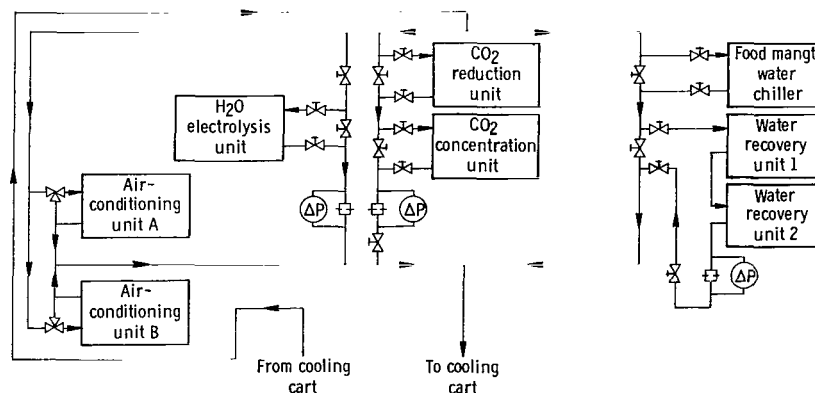
Scattered throughout the network are fixed orifices. They limit branch pressure drops to balance the network and provide pressure differentials from which flow rates may be measured. Flow rate is controlled with variable orifices placed within branches. Three service valves are used with each life support subsystem or unit. These valves control flow to individual components and permit component removal without disturbing the network balance.

The heating fluid is an energy source except in the CO₂ reduction unit. In this unit the fluid serves as an energy sink (except during startup) by removing heat from the exothermic Sabatier reaction.

Cooling fluid. - The distribution network for process cooling fluid (fig. 6(b)) is similar to that for the process heating fluid. It has four parallel branches. Components that



(a) Heating fluid network.



(b) Cooling fluid network.

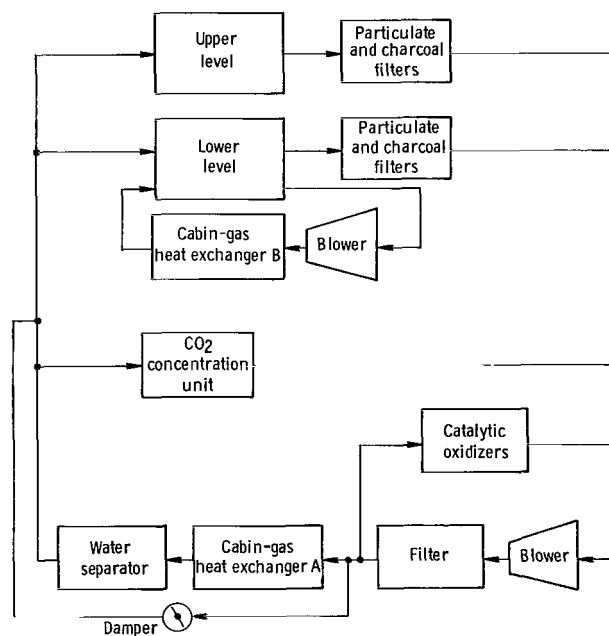
Figure 6.- ILSS energy-transport-fluid distribution.

do not need cooling fluid at its coldest temperature are downstream and in series with those that do. The two air-conditioning units are in a parallel arrangement on one branch for maximum cooling capability. Valves and orifices in the cooling network perform the same functions as those in the heating network. The cooling fluid removes heat from gaseous or liquid working fluids. In most instances, when cooling fluid is used to remove heat from an airstream, the purpose is to lower the airstream temperature below its dewpoint and thereby cause condensation. This is the method used to collect water in the ILSS. The heat exchanger of air-conditioning unit B (fig. 6(b)), however, removes only sensible heat and therefore does not condense moisture from its airstream.

Electricity.- Electrical energy supplied to each of the subsystems is used by several components. The major electrical loads are heaters, motors, lighting, and instrumentation. An exception is the electrolysis unit. A portion of the electrical energy supplied to this unit is consumed in dissociating water molecules into hydrogen and oxygen. The remaining electrical energy for this unit is transferred directly to the cooling fluid as thermal energy or indirectly to the test-chamber atmosphere.

Air-conditioner.- The air-conditioner controls test-chamber air temperature and humidity. Heat loads from equipment and men are dissipated to the test-chamber air and removed by the air-conditioner.

The air-conditioning circuit is schematically illustrated in figure 6(c). It can be seen that heat exchanger A is designed for heat loads of both levels in the test chamber.



(c) Air-conditioning circuit (simplified).

Figure 6.- Concluded.

Because of the higher heat loads in the lower level, the additional cooling capacity of heat exchanger B is needed. Process-air heat gains taking place in the CO₂ concentrator and catalytic oxidizer ducting are removed by heat exchanger A.

Flow controllers, which alter cooling fluid through the heat exchangers and the amount of air bypassing heat exchanger A, are automated. These devices keep the upper- and lower-level air and the air exiting from heat-exchanger A at preselected temperatures. Humidity in the test chamber is not controlled to a preselected value. However, the air-conditioner was designed such that relative humidity would stay within acceptable limits.

ACQUISITION OF ENERGY-TRANSFER-RATE DATA

Data from which energy transfer can be determined are obtained with subsystem performance instrumentation. A schematic diagram of the ILSS data acquisition system is shown in figure 7. Continuous low-voltage signals proportional to the measured quantity are generated by sensors attached to the subsystems. The sensors are connected to

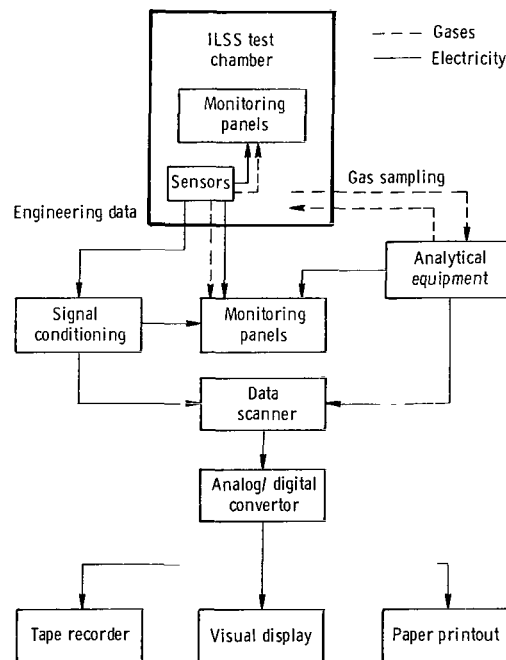
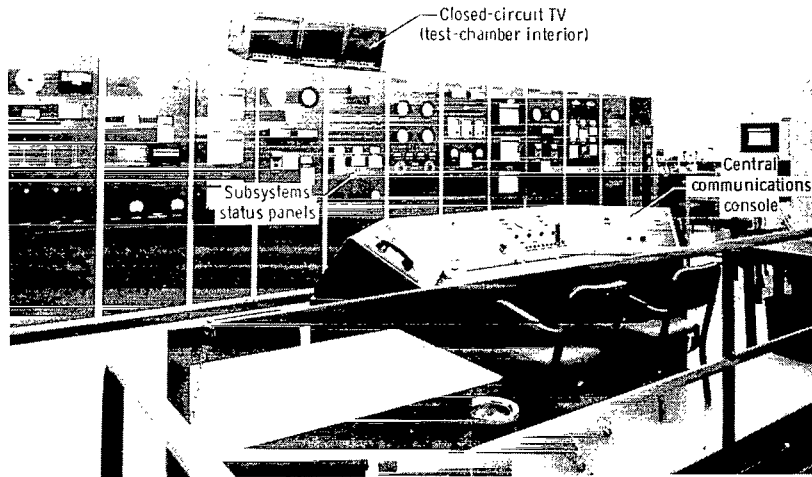


Figure 7.- ILSS data acquisition system.

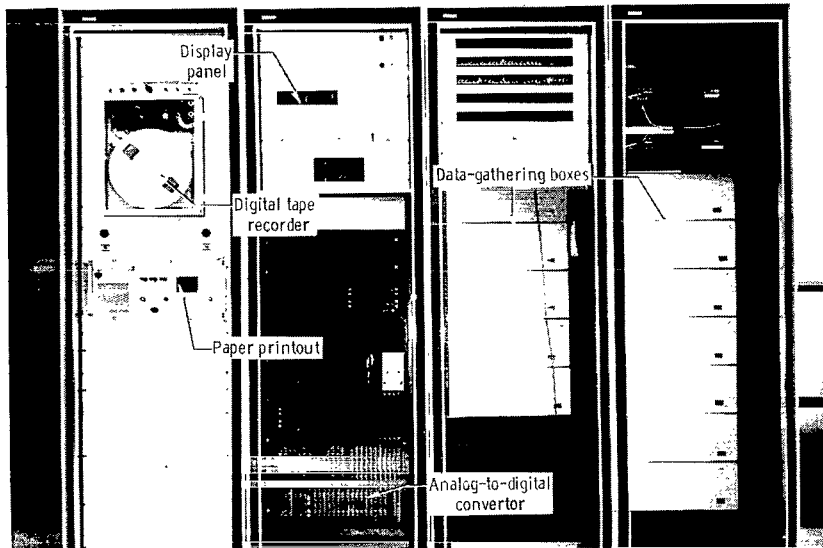
both real-time indicators and the automatic recording subsystem. Photographs of the monitoring facility, including typical indicators, and the automatic data-acquisition recording subsystem are shown in figures 8 and 9, respectively. In addition to this external equipment, other instruments and associated indicators are installed in the test

chamber for monitoring by the crew. However, practically all the data used in determining ILSS energy transfer rates were obtained from the external automatic recording subsystem.



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Figure 8.- ILSS monitoring facility.



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Figure 9.- ILSS automatic data-acquisition recording subsystem.

Data Processing

A digital computer program is required to convert recorded data into a useful format. The program which was written for this purpose reads the magnetic tape, converts the digital information on the tape to useful physical units, tabulates the converted data to the test-time base, and computes daily lows, highs, and averages for each data channel.

Measurements needed to establish energy transfer include electrical power consumption, liquid and gas flow rates, and liquid and gas temperatures. Mathematical formulas describe measurement characteristics of required instruments and are programmed for the digital computer. The programmed algorithms reduce data from linear and nonlinear response instruments on the basis of instrument calibration information for each data channel.

Calibration data of linear response instruments are used to establish straight-line curve constants. The constants are stored in computer memory for use during data processing. Calibration data of nonlinear instruments are used to derive polynomial expressions from curve fitting by the method of least squares. Coefficients for these expressions are stored in memory and are used during data processing. It was learned during the study that these techniques require less computer time and calibration data and give results comparable to interpolation methods normally used.

Measurement Accuracy

Differences between sensor measurements and the final computed energy transfer rates are due to several factors. An assessment of these sources of error is a matter of conjecture that is oftentimes based upon the expertise of the thermal analyst doing the work rather than quantitative analyses. It is possible, however, to define accuracies of instruments used to measure the quantities required for energy-transfer-rate computations. These accuracies are defined in this section. The other sources of error are indicated in subsequent sections, but no attempt is made to quantitatively establish their effect upon final results.

Prior to an ILSS test the applicable instrumentation system is checked for operational accuracy, and calibration curves of instruments are reestablished. These curves produce calibration data which are within 3 percent of the actual values being measured. Curves fitted to calibration data are accurate to within 2 percent of the largest measured quantity of a single set of calibration data. Overall accuracy of the system is thus considered to be within 5 percent of the actual measured quantities.

Another measurement error is the dead band of thermocouple cold-junction references that have on/off controllers. Temperature measurements made with this system are periodic and dependent upon controller dead band. Typical measurements shown in

figure 10 indicate that low temperatures are affected more by dead band than high temperatures. If temperature measurements are made frequently and the dead-band characteristics of the controllers remain unchanged, measurement error can be eliminated by averaging data over one or more control cycles.

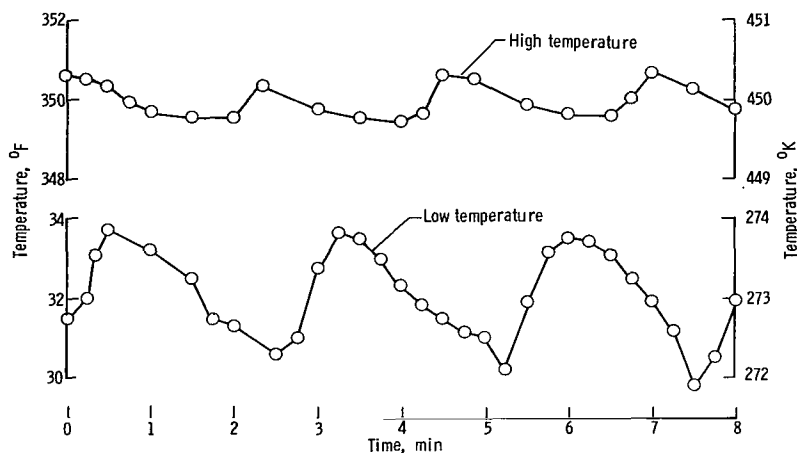


Figure 10.- Effect of thermocouple cold-junction references on temperature measurement.

Since it was not originally planned to use real-time indicators in the test chamber for this study, an effort to ascertain their accuracy was not undertaken. It is estimated, however, on the basis of the types of sensors and indicators and their use, that inside manually recorded data are within 10 percent of actual values. A large portion of this error has been attributed to difficulty in reading small scales of real-time indicators.

Data Corrections

After making preliminary calculations of energy transfer rates by using data recorded on magnetic tape, some minor measuring anomalies were discovered that produced unacceptable results. In most of these instances manually recorded data were used to replace the automatically recorded data. There were two instances, however, when required measurements were not recorded manually or by the data management system.

The voltage to module B in the electrolysis unit and electrical power for catalytic oxidizer No. 2 were not measured. Two different schemes were devised to obtain data for these parameters. Voltage requirements for module B in previous tests were reviewed along with those for modules A and C. A constant value of 32.5 volts was then selected as being representative. Similarly, previous test data from catalytic oxidizer No. 1 were reviewed. They showed a persistent linear relationship between heater power

and catalyst-bed outlet temperature. This relationship was assumed to exist also for oxidizer No. 2; thus its power consumption can be determined from measured operating temperatures.

Corrections have the most significant impact upon results of the study when an energy transfer rate is determined from both manually and automatically recorded data for a given interval of time. Manually recorded data were obtained at a slower rate than the automatically recorded data and are assumed to be invariant if the interval of interest is less than 2 hours. Otherwise, they are averaged for the interval of interest. Energy transfer rates affected by this assumption are indicated in the section "Results and Discussion."

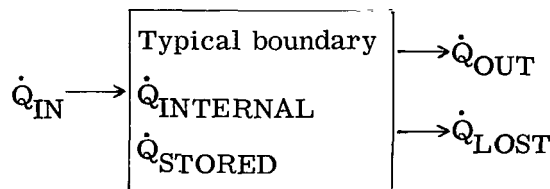
Data Sampling Rates

Data were taken during the 28-day manned test and the 4-day intermittently manned test at different sampling rates. An analysis of the data indicated that tape recordings must be made once every 5 minutes, or faster, to record all subsystem transients. Faster rates insure that all transient rates are recorded, but tape usage is excessively high. Transient energy transfer rates presented in this report were obtained from data recorded once every 2 minutes over a $1\frac{1}{2}$ -hour period of manned testing. Energy transfer during the intermittently manned test was determined from data recorded once every 5 minutes. Manually recorded data were obtained once every 2 hours.

DETERMINATION OF ENERGY TRANSFER

Energy Boundaries

In order to determine the total system energy transfer and to quantify the transfer at the major interfaces where it occurs, discrete boundaries were established as indicated in the following sketch:



The majority of the boundaries occur at subsystem or unit level; however, other specific boundaries had to be established to account for the total energy transfer. The boundaries used for the energy transfer study are shown in figure 11.

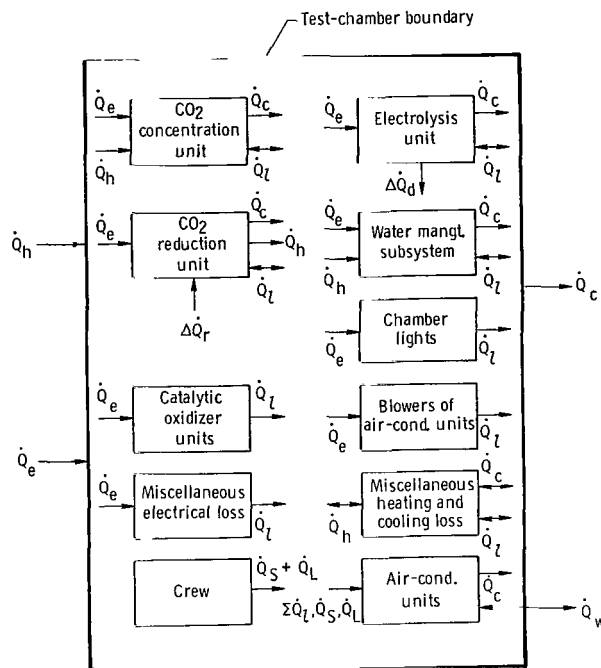


Figure 11.- Selected ILSS energy transfer boundaries.

Energy typically flowing into a boundary \dot{Q}_{IN} consists of thermal energy from the process heating fluid and electrical energy. Internal energy $\dot{Q}_{INTERNAL}$ results from exothermic or endothermic processes of some subsystems. Energy typically flowing from the boundary includes the thermal energy rejected to the process cooling fluid \dot{Q}_{OUT} and the thermal energy lost to the test-chamber atmosphere \dot{Q}_{LOST} . As a result of ILSS operating characteristics, incoming and outgoing energies of thermal transport fluids have a periodic nature, as does internal energy flow. Thus, some boundaries are always in a transient state of energy transfer, so to complete an energy balance, stored energy \dot{Q}_{STORED} must be included to account for time-variant differences in energy flow across the boundary.

Sufficient measurements were made to determine incoming electrical and heating fluid energy flow as well as internal and cooling fluid energy flows. Stored energy can be estimated from transient temperature-variation analysis for solids. Since much of the energy transfer takes place in plate-fin or tube-fin heat exchangers, the temperature variation through an infinite flat plate or slab for single-direction heat flow is considered to be a reasonable analytical model. With the assumption that such a plate suddenly

undergoes a temperature change at one of its surfaces, the time interval before the other surface reaches thermal equilibrium can be established. A semiempirical solution to this problem is outlined in reference 8. On the basis of this solution methodology, it was found that only approximately 0.5 second will elapse before equilibrium is reached for an aluminum plate of 0.318-cm (0.125-inch) thickness and a step change in surface temperature of 430° K (315° F). This period is so short that stored energy will be extremely small, so it is neglected in the remainder of the study. As a consequence, lost energy transfer rates \dot{Q}_{LOST} are found by applying the conservation-of-energy law to subsystem boundaries.

Internal energy changes are important in determining the energy transfer in the CO₂ reduction unit and the electrolysis unit. In the Sabatier CO₂ reduction unit, the reaction between hydrogen and carbon dioxide is exothermic and is treated as an internal energy change $\Delta\dot{Q}_r$. A portion of the electrical energy consumed in the electrolysis unit $\Delta\dot{Q}_d$ goes directly to the dissociation of hydrogen and oxygen gases from water and is treated as an energy loss from the unit. Latent and sensible heat loads from test-chamber occupants are indicated as energy transfer rates \dot{Q}_L and \dot{Q}_S from a boundary denoted in figure 11 as "crew." These rates are internal to the test-chamber boundary, as are the internal energy flows of the electrolysis and CO₂ reduction units.

The "miscellaneous electrical loss" boundary (see fig. 11) accounts for electrical energy not consumed in subsystems. The miscellaneous electrical loss is the difference between the total measured electrical consumption and the total electrical utilization of subsystems. Similarly, process heating and cooling energy not transferred within subsystems is indicated by the boundary called "miscellaneous heating and cooling loss." Energy transfer at these two boundaries includes all the electrical and thermal losses in wiring and plumbing between subsystems and the energies utilized in operating subsystems on the upper test-chamber level. Subsystems located on the test-chamber upper level were not considered as boundaries since they are infrequently exercised and have energy demands significantly less than subsystems on the lower level.

Equations

Operation of the ILSS results in the lowering or raising of process fluid temperatures as energy is exchanged across boundaries. The energy release or gain from these temperature changes can most accurately be calculated by $dQ = mc_p(T)dT$. The term $c_p(T)$ of the equation is relatively invariant for air within the temperature range of interest and is therefore assumed to be constant. Polynomials of the form $(a + bT + cT^2)$ were found from curve fitting specific-heat data to determine c_p for heating and cooling fluids.

Subsystem electrical consumption is found either by direct measurement of power or by determining the product of current and dc voltage, where current and voltage are measured. Dissociation energy for electrolysis may be determined from theoretical considerations and the design of the electrolysis unit. It can be theoretically shown that an electrical potential of 1.23 volts is required (ref. 9). The amount of current going directly into electrolysis could not be measured during testing; however, current is directly proportional to oxygen generation. On the basis of these factors an actual value of heat of dissociation (h_d) is determined to be 14.2 MJ/kg (6120 Btu/lb). Dissociation energy transfer may then be determined from

$$\Delta\dot{Q}_d = h_d \dot{m}_{O_2} \quad (1)$$

where the oxygen production rate \dot{m}_{O_2} is a measured quantity. Electrical energy consumed by the chamber lighting is found by determining the number of lights used and their power rating.

The sensible energy transfer rate of men in the test chamber can be expressed as (ref. 10)

$$\dot{Q}_S = N(523 + 1.625T_{LL} - 0.06875T_{LL}^2) \quad (2)$$

where \dot{Q}_S is in Btu/hr and T_{LL} is in °F. (In order to obtain \dot{Q}_S in J/s, multiply the value in Btu/hr by 0.293.) The latent thermal energy transfer rate is from test-chamber occupants and any other source of water vapor in the test chamber. Therefore, it is based upon daily water removal rates from the air-conditioner. At the controlled exit temperature of the air-conditioner, the energy required to fully condense water from completely saturated air is 2.5 MJ/kg (1072 Btu/lb). The latent thermal energy transfer rate may then be determined from

$$\dot{Q}_L = h_L \dot{m}_V \quad (3)$$

One other equation is needed. It is used to determine the internal energy of the CO₂ reduction unit. At chemical equilibrium the Sabatier reaction liberates 3.82 MJ/kg (1640 Btu/lb) of CO₂ (ref. 11). Since the daily amount of CO₂ that is reacted is known, the energy transfer rate can be calculated from

$$\Delta\dot{Q}_r = h_r \dot{m}_r \quad (4)$$

RESULTS AND DISCUSSION

Averaged Energy Transfer Rates

In figures 12 and 13 energy transfer rates calculated from averaged data of manned and intermittently manned tests are shown. All energies to the left of "Boundary" are typically energy sources, and energies to the right are typically energy sinks. Lost energy \dot{Q}_{LOST} is transferred to test-chamber air from subsystems. Lost energy not removed by the air-conditioner is transferred from the test-chamber air through the chamber wall to building air. At the bottom of each figure is the total energy balance of the test-chamber boundary. For either test about 10 kW of thermal and electrical energy was supplied to operate the ILSS. Only 35 percent of this total energy is directly rejected

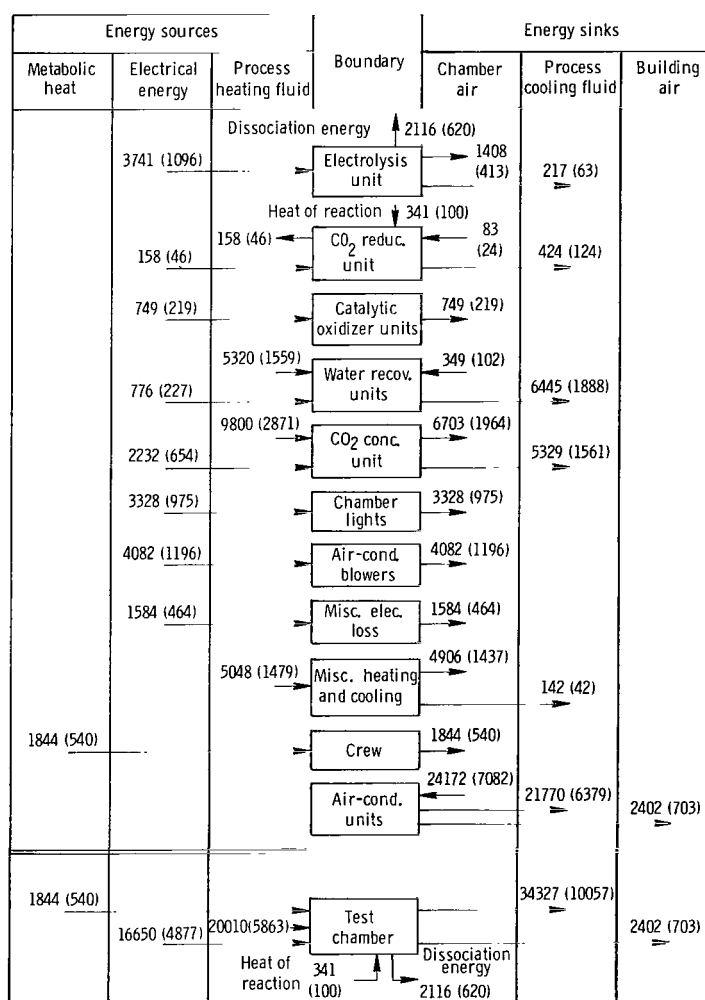


Figure 12.- Averaged energy distribution for 5-hour period of 28-day manned test. (Energy-transfer-rate values are given in Btu/hr and parenthetically in J/s.)

to the cooling fluid circulated through the various subsystems and units. The remaining 65 percent is energy lost to the test-chamber air.

In figure 13 it can be seen that the metabolic energy transfer rate is zero, although the test chamber was manned for short periods to make minor equipment adjustments. On these occasions two men occupied the chamber. Occupancy was only 6.4 percent of total test time. Therefore, metabolic energy was very small compared with other energy levels and was consequently ignored. During the manned test a four-man crew was used 100 percent of the time and, as can be seen in figure 12, they produced significant thermal metabolic energy.

Comparison of the two tests indicates only minor differences in energy transfer rates. One notable exception is the electrical energy of the blowers. The higher power

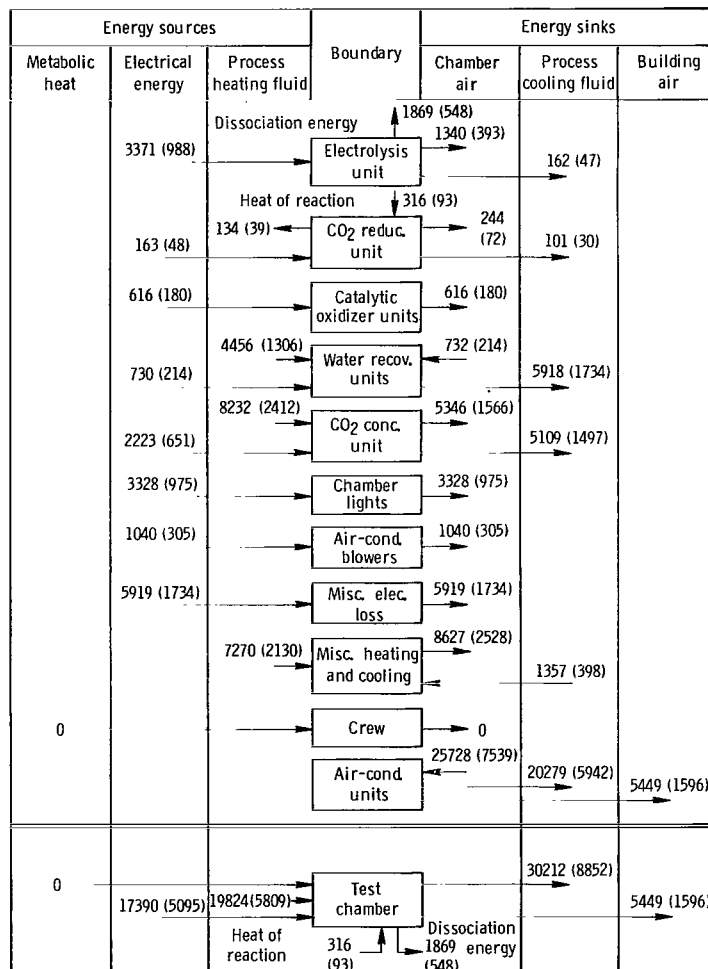


Figure 13.- Averaged energy distribution for 4-day intermittently manned test. (Energy-transfer-rate values are given in Btu/hr and parenthetically in J/s.)

consumption during the manned test was the result of particulate filter clogging, which was found at test termination. Clean filters were used during the intermittently manned test.

Further comparison of the two figures indicates that much of the energy loss was transferred to the test-chamber air and removed by the air-conditioner. Losses not removed are rejected through the test-chamber wall to the building air. The fact that 894 J/s (3047 Btu/hr) more energy is rejected to building air during the 4-day test than the 28-day manned test, although averaged test-chamber air temperature was the same during both tests, was probably due to cooler seasonable air surrounding the test chamber during the 4-day test. Seasonable temperature changes, although small, have a significant effect on wall energy transfer because of the relatively large wall area – approximately 898 m² (9670 ft²).

Transient Energy Transfer

A number of controllers and timers are used in ILSS subsystems. These devices influence ILSS energy transfer, and their effect upon selected energy transfer rates has been plotted from a 1½-hour period of data continuously recorded during the manned test.

Test chamber.— Figure 14 shows source and sink energy transfer rates across the test-chamber boundary. The CO₂ concentration unit cycles every 40 minutes. The effect of its operation is evidenced by the 40-minute interval between repeated energy transfer spikes in the two thermal fluids. Periods of maximum energy transfer from the cooling fluid are slightly out of phase with periods of minimum energy transfer from the heating fluid

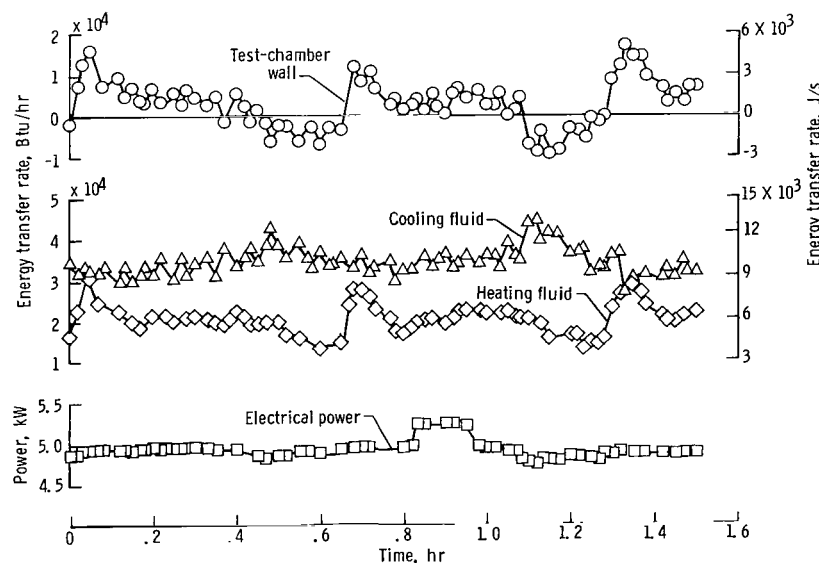


Figure 14.— Test-chamber energy transfer rates during an interval of ILSS manned testing.

fluid. The difference in energy transfer between the heating-fluid and electrical-power sources and the cooling-fluid heat sink was used to establish the energy flow through the test-chamber wall. Because of the thermal storage of the test-chamber air and wall and the time lags between transient subsystem energy losses to the test-chamber air and wall, transient energy flow across the wall is not exactly as shown. Some thermal lags involved in this energy flow are indicated in subsequent figures.

Subsystem energy losses and air-conditioner performance. - Figure 15 contains plots of energy transfer rates for the three kinds of units whose energy losses are largest. The rather severe thermal spikes evident in the plot for the CO₂ concentration unit result from periodically diverting thermal transport fluids to the various heat exchangers in this unit. There is a section of ducting without insulation in the water recovery units that is colder than the surrounding air; negative portions of the curve for these units depict periods during which energy is transferred from test-chamber air to this ducting. The energy transfer rates for the electrolysis unit are not entirely the result of its operation. Temperatures of the cooling fluid passing through this unit are in the region where thermocouple-reference-controller dead band has a pronounced effect upon measurement and subsequent energy transfer calculations.

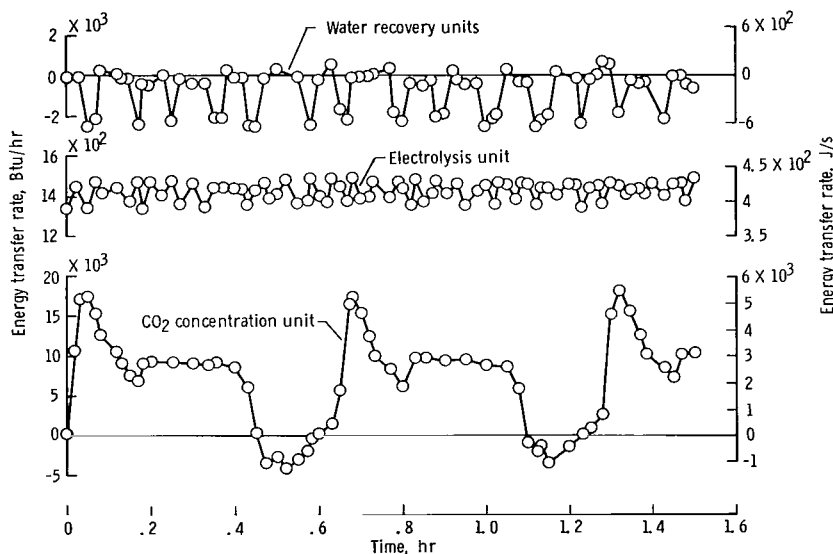


Figure 15.- Rates of energy transfer between units and test-chamber air during an interval of ILSS manned testing.

The total-energy-loss curve shown in figure 16 includes all thermal losses to the test-chamber air. These losses are assumed to be instantaneously transferred directly to the test-chamber air. The 40-minute cyclic variation of the curve shows that the CO₂ concentrator is the unit having the greatest influence on total energy loss.

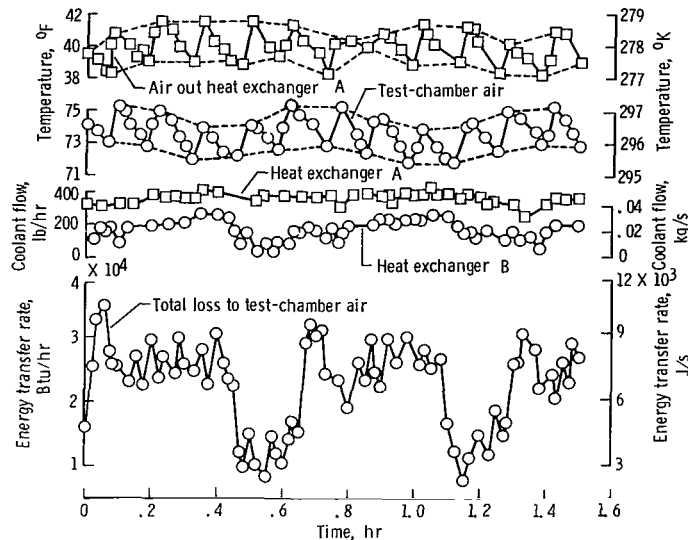
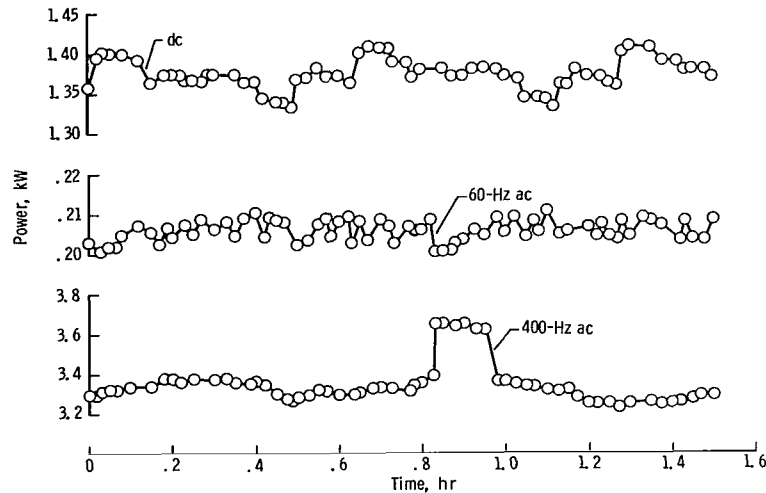


Figure 16.- Air-conditioner performance during an interval of ILSS manned testing.

Also shown in figure 16 are air-conditioner performance curves. Coolant flow through air-conditioner heat exchangers A and B is automatically controlled and should be responsive to test-chamber-air thermal loading from energy losses within the chamber. Temperature of the test-chamber air should be maintained at the preselected control-point temperature. (Unfortunately, the control-point temperature for the interval shown was not recorded.) The test-chamber-air curve shows cyclic variations of two different frequencies. The variation illustrated by the band between dashed test-chamber-air curves has the same period as that of total energy loss; thus, the indication is that a portion of total energy loss is being transferred to the test-chamber air. Automatic controllers are not responsive enough to prevent these temperature fluctuations; however, the fluctuations are minor. Neither the flow controller of heat exchanger A nor that of heat exchanger B responds to the test-chamber thermal loading illustrated by the solid-line temperature curves.

By referring to figure 15, it is seen that the two temperature response curves of figure 16 have the same frequency as the transient energy loss of the water recovery units, but this frequency is not evident in the total loss to the test-chamber air (fig. 16). This fact indicates that the mechanism of energy transfer causing the more rapid test-chamber-air temperature variations is not due to heat losses from the water recovery units to the test-chamber air. Other transient energy factors are presented subsequently to identify the driving function and coupling mechanism.

Electrical power.- The amount of each type of electrical power used in the ILSS is plotted in figure 17(a). Much of the electrical equipment that is periodically activated



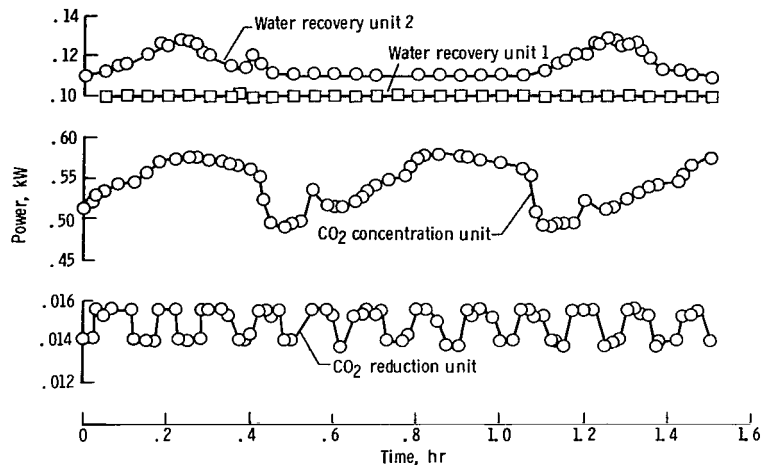
(a) Total power supplied from each source.

Figure 17.- Power consumption during an interval of ILSS manned testing.

operates from 28-volt dc or 208-volt 400-Hz ac electricity. These two sources comprise 95 percent of the total power consumption. The choppiness of the 60-Hz ac power is not the result of subsystem operation but is indicative of commercially supplied power at the test facility. Solenoid valves and the electrolysis unit use dc power, whereas servomotors, pumps, and blowers use 400-Hz ac power. As a result, the dc power curve tends to be a square wave compared with the smoother 400-Hz curve. It can be seen that the power plateau between 0.83 and 0.97 hour (illustrated in fig. 14) results from operation of a 400-Hz device. A referral to the test conductor's log revealed that the waste management subsystem was exercised during this period. The increase in power is that necessary to operate the blower—water-separator combination of this subsystem.

Not immediately apparent in figure 17(a) is the previously noted behavior of test-chamber-air temperature. If this behavior results from subsystem operation, the same frequency variation should appear in subsystem power consumption curves. Subsystem utilization of 400-Hz power is pictured in figure 17(b).

The CO₂ concentration unit has a blower and vacuum pump that use most of the 400-Hz power. Variations in the power profile for the CO₂ concentrator are cyclic and are coincident with programmed operation. The gradual slopes are attributed to pressure changes as CO₂ is outgassed during the desorption cycle. Blowers in the water recovery units are also operated from the 400-Hz power. Air circulated by them is used to rotate centrifugal water separators. Occasionally, slugs of water are trapped within the separator jacket and create drag forces on the impeller. It is suspected that the two peaks evident in the figure were produced by such slugs.



(b) Subsystem 400-Hz power consumption.

Figure 17.- Concluded.

A solenoid valve in the CO_2 reduction unit diverts heating fluid to or from the unit to keep the Sabatier reactor at a preselected temperature. The action of this valve, which is controlled by a thermostat that senses reactor temperature, is evident in the reduction-unit curve. The curve has the same frequency as that of test-chamber-air temperature (see fig. 16), the indication being that the CO_2 reduction unit is the driving function. Identification of the coupling mechanism may be determined from other results. The first medium to be affected is the process heating fluid, since it is this fluid that is being modulated by the Sabatier reactor temperature controller.

Heating fluid.- Heating-fluid energy transients of individual subsystems are illustrated in figure 18. Curves for the concentration and reduction units are not entirely accurate, as constant flow rates were used to calculate energy transfer in these two units. Energy gained in the reduction unit is in phase with operation of its temperature controller (fig. 17(b)).

Water recovery units are in parallel and are serially connected to the heating fluid exiting from the reduction unit. The pulsed flow rate and fluid temperatures, however, only affect energy transfer from the heating fluid in water recovery unit 1. The effect is interesting. Instead of a 14.67-J/s (50-Btu/hr) peak-to-peak variation as at the reduction unit, the amplitude has been magnified by a factor of approximately 20 (see fig. 18). The temperature and flow pulsations do not reach the water recovery unit at the same instant. As a result, the frequency of energy pulses is practically twice that for the reduction unit. Energy pulsations are damped in unit 2 because of the lower rate of flow through it.

Examination of the concentrator curve shows that the pulses do not alter heating-fluid energy transfer within the concentrator. It has already been shown that coupling

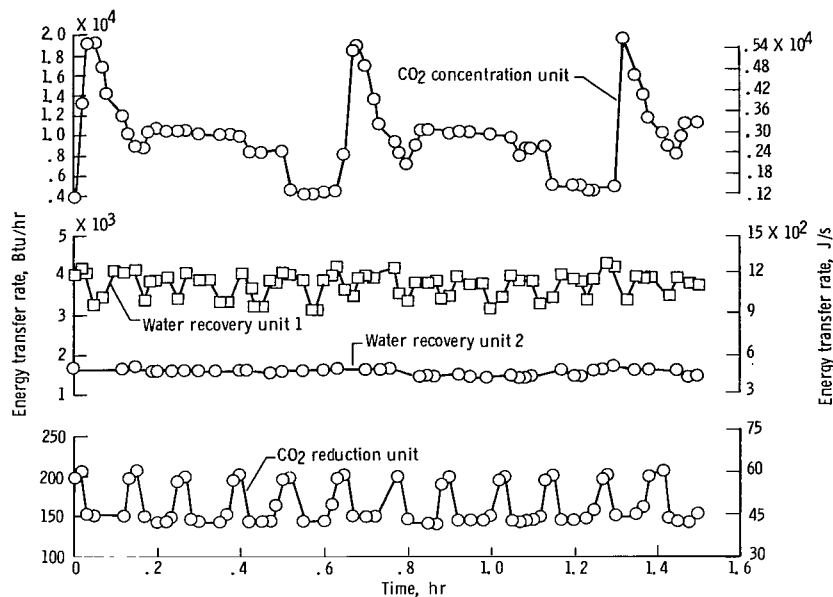


Figure 18.- Subsystem heating-fluid energy transfer rates during an interval of ILSS manned testing.

does not occur between water recovery units and the test-chamber air. The only other energy transfer medium that may be involved is the process cooling fluid.

Cooling fluid.- Parameters affecting energy addition to the cooling fluid are pictured in figure 19. The relatively high frequency of the supply curve is attributed to two factors: (1) action of the controllers in the cooling cart, and (2) the influence of

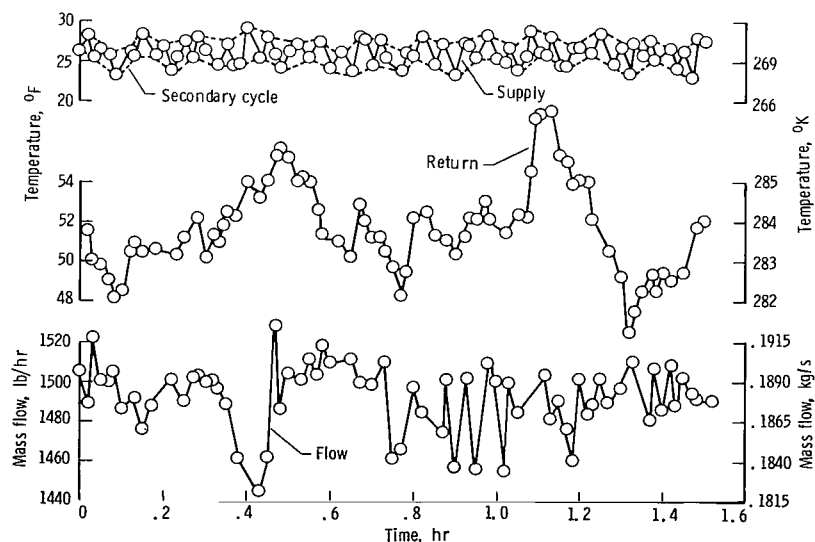


Figure 19.- Cooling-fluid energy transfer parameters during an interval of ILSS manned testing.

thermocouple-reference controllers on low-temperature measurement (fig. 10). The secondary-cycle band plotted on this curve has the same frequency but is out of phase with test-chamber-air temperature. The return-temperature curve has mainly a periodic variation of 40 minutes, with a secondary variation coincident with the dashed secondary-cycle supply curve, the indication being that it is influenced by both the CO₂ concentration unit and the CO₂ reduction unit.

Energy coupling can thereby be traced to the water recovery units. Pulsations of thermal energy from the heating fluid of the CO₂ reduction unit are transferred to the cooling fluid by the airstream that serially passes through the heat exchangers and condensers of the water recovery units. The cooling cart does not maintain a constant supply temperature. Consequently, cooling fluid supplied to ILSS air-conditioners has a cyclic variation of 1.66° to 2.77° K (3° to 5° F) that is manifested in the cabin air as a 1.66° K (3° F) cyclic temperature variation lagging the cooling cart thermal response by approximately 6 minutes.

CONCLUDING REMARKS

Data have been obtained from manned and intermittently manned tests of an integrated life support system (ILSS) at the Langley Research Center to permit a study of energy transfer of the system and its major subsystems.

The approximately 10 kW of electricity and thermal energy used for ILSS operation should not be construed as being indicative of regenerative-life-support-system energy demands, as no attempt was made during ILSS design to optimize energy requirements.

In view of the 35-percent utilization of energy supplied to the ILSS and the identification of major thermal inefficiencies, it is expected that basic improvements can be made to subsystem design, fluid transport plumbing, and accessories such as chamber lighting in order to reduce the power input. The relatively large amounts of energy which were lost serve to emphasize the importance of giving thermal efficiencies serious consideration during the initial design of regenerative life support systems.

It was found from the study that expected coupling between thermal transport fluids does exist and that it influences the test-chamber thermal environment. Control of air-conditioner coolant flow to maintain an acceptable test-chamber air temperature resulted in fluctuations of 1.66° K (3° F), which appear to be acceptable. Other types of controllers more responsive to variations of chamber-air thermal loading can be designed for this function. Regenerative-life-support-system design should include analyses of thermal coupling and its influence on test-chamber or spacecraft-cabin temperature. On the basis of the influence of the automatically liquid-cooled Sabatier reactor on the thermodynamics of other ILSS subsystems, it would appear that future regenerative life support systems should use passively air-cooled reactors.

The automatic data acquisition and computer processing techniques used in the study produced measurements of acceptable accuracy. These techniques vastly reduced the time required to acquire and manipulate data manually and should be used in future testing.

Energy balances found from measuring source and sink energy properties, with thermal equilibrium assumed, provided a method of establishing energy-transfer closure. Accuracy of this method could not be quantitatively proven, but subsequent results were shown to have a predictable behavior and are considered adequate for revealing baseline energy demands. In addition, results from this method yield experimentally derived information that will be used in analytical life-support investigations to provide a realistic model of typical life-support-system thermodynamics. Utilization of this model will permit additional studies of energy transfer mechanisms and their control such that future regenerative life support systems can be developed with improved thermal efficiencies.

Langley Research Center,
National Aeronautics and Space Administration,
Hampton, Va., January 19, 1971.

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